Distributed quantitative evaluation of 3D patient specific arterial models

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Abstract

In this paper we describe a new system for the 3D reconstruction and distribution on the net of models for vessels structures. The system is specifically designed to support measurements of medical interest. We describe 2D and 3D segmentation methods implemented and the procedure used to build interactive VRML97 models. The experimental section presents a comparison between segmentation methods, and a first application to surgical planning for endovascular repair of Abdominal Aortic Aneurysms.

1. Introduction

Computer vision, virtual reality and Web technologies can really have clinically relevant applications. In this paper we present a novel application using customized image processing technique and web technologies to help surgeons in diagnosis and pre-operative measurements of 3D structures. In detail, we used 3D segmentation methods, VRML and javascript, to assemble patient specific models of vessels that allow surgeons to measure inherently 3D quantities that are important, for example, to surgical planning, e.g., the angles between vessels at the iliac bifurcation. The models are reasonably compact in size, with an average size of few hundred kilobytes, and can be quickly transferred across Internet. The data sent is essentially the vessel surface geometry plus embedded code and pre-computed tables to support the measurements.

2 Segmentation and 3D reconstruction

In order to perform measurements on vascular geometries (and also to support other virtual reality and numerical simulation applications) we designed a specialized data structure that we named “Arterial Tree”. An Arterial Tree is defined as the union of a complete surface mesh describing the vessels internal surface, and a skeleton joining series of 1D lines representing the vessels centerline. This data structure allows us to realize precise measurements of vessel length abd to simplify the estimate of a plane perpendicular to the vessel; We implemented three methods for the reconstruction of the AT structure and developed an user friendly interface to control the use of these methods and other image processing tools. Methods are:

A: Segmentation from 2D contours: The dataset is cut with series of planes approximately directed along the vessel branches directions. Contours are extracted with snake balloons [2, 3] and joined in simple tubes. Finally, tubes are glued together to build the complete tree. The centerline is built by generating a spline passing through the centers of mass of the extracted contours.

B: Segmentation from isosurfaces and automatic centerline extraction: Thresholding and marching cubes [7] are used to compute the vessel surface, while the centerline is automatically extracted with an algorithm initialized giving a point inside the vessel and described in section 2.3.

C: Segmentation from Simplex Balloon and automatic centerline extraction: Simplex balloons [4] are a deformable surfaces in the 3D space. Initializing surfaces as small spheres inside the vessels and choosing the correct forces inflating and driving surface points to the vessel border, we can obtain a smooth vessel surface. The same algorithm as in method B is used for the centerline extraction.

The automatic centerline extraction required bu methods B and C directly works on the voxel data. The algorithm, derived from the voxel coding technique introduced in [5], works on the result of a 3D region growing algoritm started from a seed inside the vessel and is based on elaborations on two distance maps: the “distance” of each internal point from the connected region boundaries and the “distance” of each internal point from the starting point of the segmentation or “seed point”.

3 VRML97 measurable models of vessels

VRML97 is a powerful language to describe 3D scenes and it is the standard language for Virtual Reality on the web. VRML97 plug-ins for Internet Explorer and Netscape Communicator (i.e. Cosmo Player (www.cai.com/cosmo)

or Cortona (www.parallelgraphics.com)) are available on the net and can be downloaded at no charge. We tested our code with Cosmo Player 2.1 for Microsoft Windows 98/NT both with Netscape and Internet Explorer. Using a perl script developed for the purpose, we automatically convert models of arterial trees representing abdominal aortic aneurysms into VRML97 files with hidden JavaScript code enabling the user to use the browser to perform quantitative measurements.
The VRML97 language specification includes a particular node, called `Script`, that is extremely powerful. It makes possible to call a custom script or a Java routine changing values of other VRML nodes.

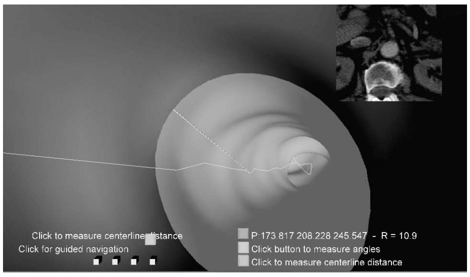

Figure 1. The VRML97 model can be inspected, navigated and measured from any PC with a web browser and a plug-in. Here a "virtual endoscopy" with radius measurement is shown.

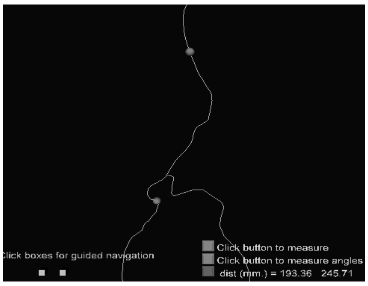

Figure 2. Measurement of centerline distance: the user clicks on two pointsand the centerline path length is displayed.

Using Javascript, we implemented three methods to measure parameters useful for medical applications, as in the examples of Figg. 1,2,3.
Furthermore, we added to the scene an image viewer so that when a point on the surface or on the centerline is clicked for measurement, the image defined by the intersection of the plane perpendicular to the centerline and passing through the point clicked and the dataset is automatically shown. Images are created off-line, compressed ad stored in a common directory on the server side. Being very small

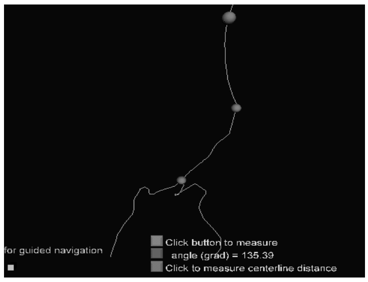

Figure 3. Measurement of centerline angles: the user places the three reference points just by clicking with the mouse on the centerline, and the angle is automatically shown.

they can be downloaded quickly. However, it is possible also to change the code to have them pre-loaded on the client side.

4 Application: Abdominal Aortic Aneurysms evaluation

In order to verify the quality and the usefulness of our model reconstructions, we have applied our system to the analysis and the endovascular surgical planning for Abdominal Aortic Aneurysms. An abdominal aortic aneurysm (AAA) is a bulge in the aorta in the abdomen [6]. AAA is a vascular disease with life-threatening implications, that is becoming increasingly common in aging populations. When the risk of rupture is high, a surgical intervention is required to repair the aorta. The standard approach is the arterial grafting in open surgery, but the mortality of this kind of intervention is high. A recently developed alternative to open surgery, is the endovascular repair, consisting in the introduction of a prosthesis with a catheter passing through the iliac artery. This procedure can be performed in a surgical or a radiological suite, but it requires a preliminary accurate assessment of patient's specific anatomy. The measurements of the geometry of the aorta is therefore extremely important. Measurements are usually done on printed 2D slides [9], and this fact can introduce large errors [6].

Using patient specific VRML97 models reconstructed with our method, any user can measure the geometric parameters of interest with good accuracy.

This is particularly interesting: in fact, other computer assisted volumetric approaches have been proposed and tested for the same purpose [6], but they require complex and proprietary software on visualization workstations. Our models allow a simple and fast measurement of the required values without the need of particular hardware or software and the measurement of aortic aneurysms seemed a good test-bed to show the usefulness of the approach chosen.

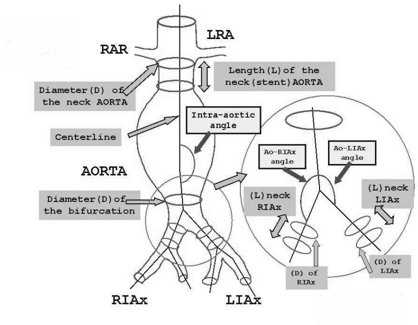

Figure 4. A large number of measurements are necessary for the planning of endovascular procedures

Moreover, this technology is ideally suited to support distributed services that improve the measurement quality (using the 3D reconstruction) and allows also collaborative surgical planning between remote sites.

5 Experimental results

5.1 Comparison of segmentation techniques

We tested the three segmentation methods described in Section 2 on different CT data sets coming from the Radiology dept. of the University of Pisa and from the Hospital of Ravenna. On datasets obtained following the standard protocols for abdominal aortic aneurysm repair planning (resolution is less than 2 mm. in the z direction and contrast liquid is injected before the acquisition so that signal to noise ratio is high) all three methods perform well and the measurements are consistent.

To analyze the robustness of the algorithm, we tested the system also on images with poor contrast and lower values of z resolution. For the isosurface extraction, a large slice spacing makes difficult to have a smooth surface and even an unique surface for small vessels. A poor signal to noise ratio causes a difficult threshold setting for discriminating the vessel lumen from the background and it makes often not possible to distinguish automatically calcium from contrast. This means that, even using median filtering and morphological closing, we cannot get automatically a good detection of the lumen and, in some cases, we obtain also discontinuous surfaces and false detections of borders.

It must be also considered that local errors are likely to be present in reconstructions. For the contour-based reconstructions, errors can be present near bifurcations, even if the image quality is good, due to possible approximation in triangulation methods. 3D balloons are affected by the necessity of finding equilibrium between image based and elastic forces, and can fail in regions where curvature is quite high and signal to noise ratio is not high. These errors do not affect, usually, the measurement of the parameters of surgical interest.

5.2 Parameter estimation form VRML models

We have taken 12 models of aortic aneurysm reconstructed from CT data provided us by the Radiology dept. of the University of Pisa and from the Hospital of Ravenna, and chosen selected parameters to be measured with a standard 2D technique currently used by surgeons and with our system. The parameters are the diameter of the aortic neck, the length of the aneurysm, the intra-aortic angle and the diameter of the bifurcation.

The data selection includes a few acquisitions with poor contrast or resolution. Therefore we decided to adopt as standard segmentation method for the VRML97 generation the 2D contour based segmentation. The comparison has been realized in the following way: for the vessel diameter, the doctor working using the standard measurement protocol on the CT slices measured the minimum of the local vessel radius, the other working on the VRML measured in four selected vessel points at the same z location, the smallest distance between the point and the centerline. We considered measurement errors equal to the voxel size in x,y directions.

The results are good (Table 1,2), except for some cases with inconsistencies at the bifurcation. In these cases this is probably due to incorrect estimates made with the "classical" method, due to varying vessel tortuosity. Errors appear to depend not only on the vertical resolution but also on vessel tortuosity. By looking at the reformatted image displayed on the browser it is possible to check the local quality of the reconstruction (see Fig.5).

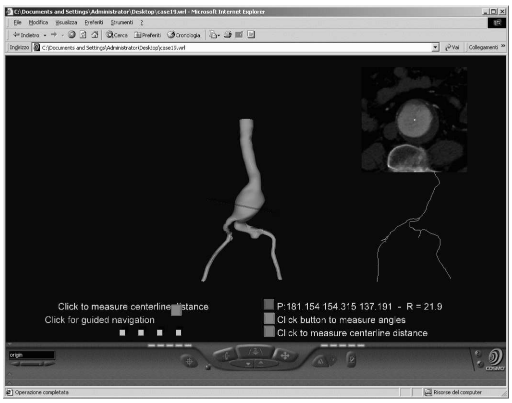

Figure 5. The pre-computed image displayed on the top left represents the reformatted slice (i.e. perpendicular to the vessel centerline), passing near the clicked point.

6 Discussion

The remote analysis of the 3D models seems extremely promising. The system allows inspections and measurement necessary for the planning of surgical interventions and it is fast, in fact the VRML measurable models can be published on the net within a few hours from the acquisition, independently from the location of the diagnostic and reconstructing centers. Model download is not usually a problem, being our VRML files sufficiently small: a geometry with 10.000 nodes is stored in a file of about 1MB, that can be gzip compressed to about 300 K, the size of a common image. It is also reliable: almost all the image processing techniques used have been tested in different contexts and applications; the preliminary tests shows also a good accuracy of the measurements if compared with other methods. Finally, it is easy to use: measuring diameters and distances is just done by clicking with the mouse on a browser window and do not require off line calculations or post processing. We think also that an approach where the segmentation is performed carefully in a controlled environment can give better results than the use of a simple algorithm as those introduced in the CT consoles by personnel not trained for the specific task.

	Neck radius(mm.)		Bif. radius(mm.)	
n	2D	VRML	2D	VRML
1	10.6 ± 0.7	10.6 ± 0.7	9.9 ± 0.7	10.4 ± 0.7
2	10.4 ± 0.7	8.9 ± 0.7	6.5 ± 0.7	6.3 ± 0.7
3	16.8 ± 0.7	17.8 ± 0.7	12.1 ± 0.7	11.3 ± 0.7
4	9.9 ± 0.7	9.9 ± 0.7	15.7 ± 0.7	15.0 ± 0.7
5	12.5 ± 0.7	11.8 ± 0.7	12.1 ± 0.7	11.8 ± 0.7
6	11.0 ± 0.7	11.0 ± 0.7	14.0 ± 0.7	13.5 ± 0.7
7	10.3 ± 0.7	9.2 ± 0.7	22.6 ± 0.7	21.4 ± 0.7
8	12.3 ± 0.7	12.5 ± 0.7	14.0 ± 0.7	14.2 ± 0.7
9	10.3 ± 0.7	9.7 ± 0.7	10.3 ± 0.7	8.6 ± 0.7
10	10.6 ± 0.7	9.3 ± 0.7	6.9 ± 0.7	7.3 ± 0.7
11	9.7 ± 0.7	8.9 ± 0.7	4.5 ± 0.7	7.6 ± 0.7
12	10.3 ± 0.7	10.3 ± 0.7	13.4 ± 0.7	12.6 ± 0.7

Table 1. Minimum radius of aortic neck and aortic bifurcation (measured carefully at the same z location using a standard 2D method, and working directly on the 3D model.

	Aneur. length(mm.)		Aortic angle(mm.)	
n.	2D	VRML	2D	VRML
1	106 ± 2	115 ± 2	139 ± 12	155 ± 12
2	88 ± 2	94 ± 2	127 ± 12	163 ± 12
3	88 ± 8	101 ± 8	128 ± 12	135 ± 12
4	110 ± 2	120 ± 2	145 ± 12	141 ± 12
5	120 ± 2	137 ± 2	135 ± 12	139 ± 12
6	129 ± 5	166 ± 5	117 ± 12	125 ± 12
7	164 ± 3	170 ± 3	124 ± 12	130 ± 12
8	129 ± 3	146 ± 3	140 ± 12	157 ± 12
9	125 ± 5	148 ± 5	131 ± 12	130 ± 12
10	120 ± 3	133 ± 3	136 ± 12	148 ± 12
11	110 ± 3	133 ± 3	139 ± 12	143 ± 12
12	120 ± 3	127 ± 3	132 ± 12	139 ± 12

Table 2. Aneurysm length and angles measured on 2D slices (only the Z component for the length) and on the VRML models.

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